Integrated Modeling Methodology Validation Using the Micro-Precision Interferometer Testbed

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Outline

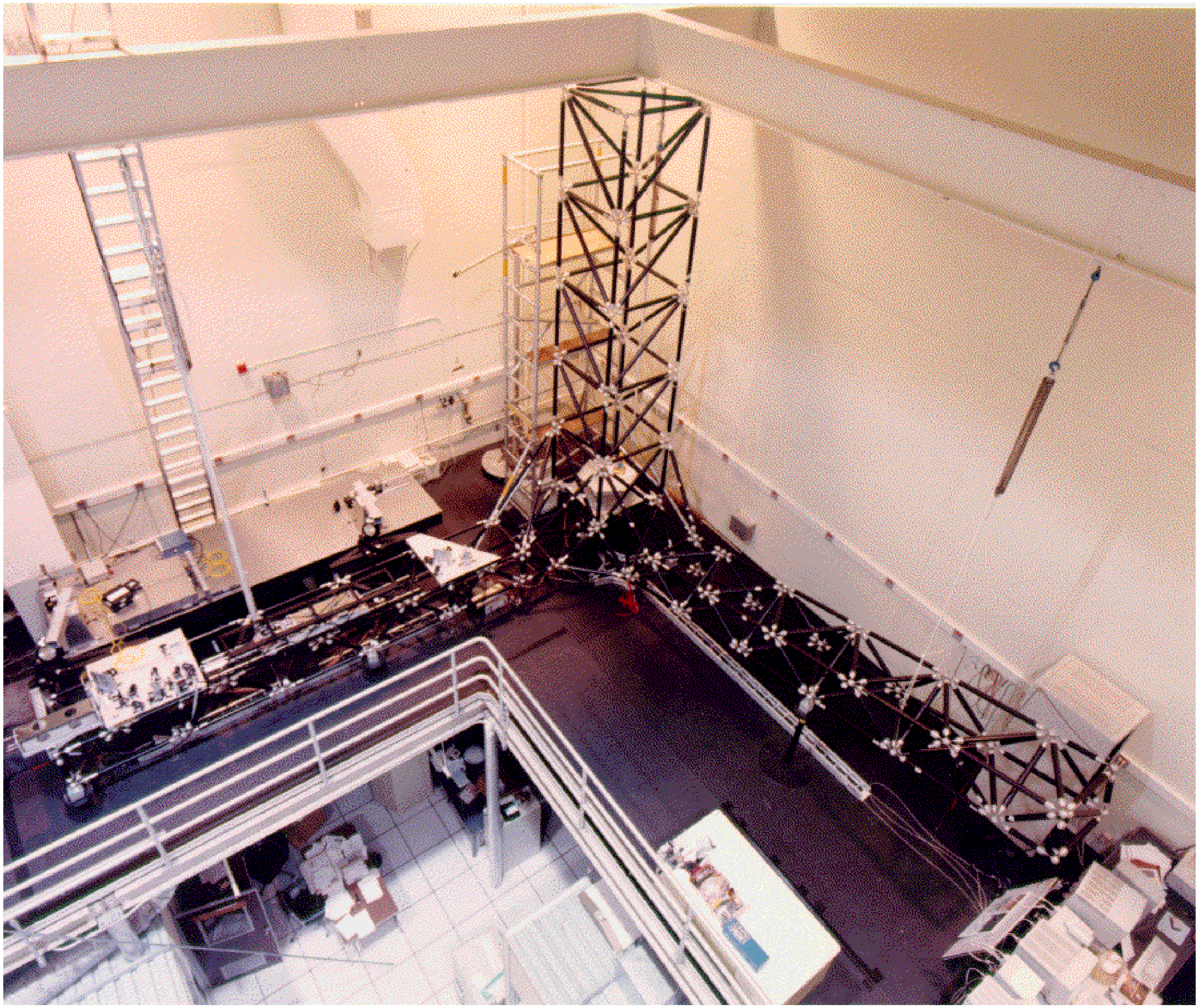
- Integrated modeling description and tools
- Micro-precision interferometer testbed
- MPI integrated model
- MPI testbed measurements
- Validation metric
- Results

- Integrated modeling refers to modeling of controls, optics, and structures in a uniform software environment.

- Integrated modeling enables true multi-disciplinary:
  - Analysis
  - Design
  - Optimization
  - Diagnosis

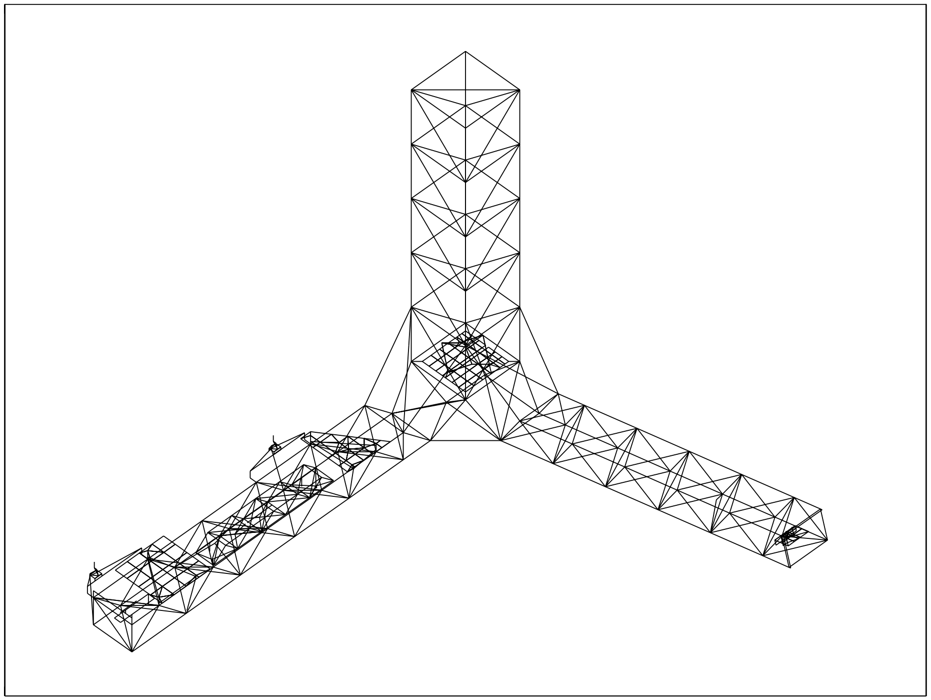
- Integrated modeling is essential for spaceborne interferometry spacecraft and mission design:
  - Interferometer performance prediction in the presence of mechanical disturbances (*nanometer* stability requirements)
  - Requirements flow-down
  - Design trades

- Integrated Modeling of Optical Systems (IMOS) software package:
  - Matlab toolbox that enables structural and optical modeling
  - Includes functions for model integration
  - Utilizes plethora of Matlab controls and analysis functions
- Controlled Optics Modelling Package (COMP):
  - FORTRAN-compiled, stand-alone program for sophisticated optical modeling (*e.g.*, diffraction and image synthesis)
  - Maintains compatibility with structural and controls models.
  - Interfaces easily with IMOS.
- IMOS and COMP have been used to evaluate *conceptual designs* of many interferometry missions: SIM, SONATA, OSI, POINTS, DLI, SITE, ISIS.
- Novel *modeling methodology* must be validated in order to have confidence in spacecraft and mission analyses.



MPI Structural Model

Finite Element Geometry



- Structural model specified in IMOS.
- Structural model consists of plate, beam, truss, and rigid body elements (RBEs).
- 2,577 total dofs: 1,832 independent w.r.t. multi-point constraints
- **Experimentally determined element properties** consistent with validation of modeling *methodology*.

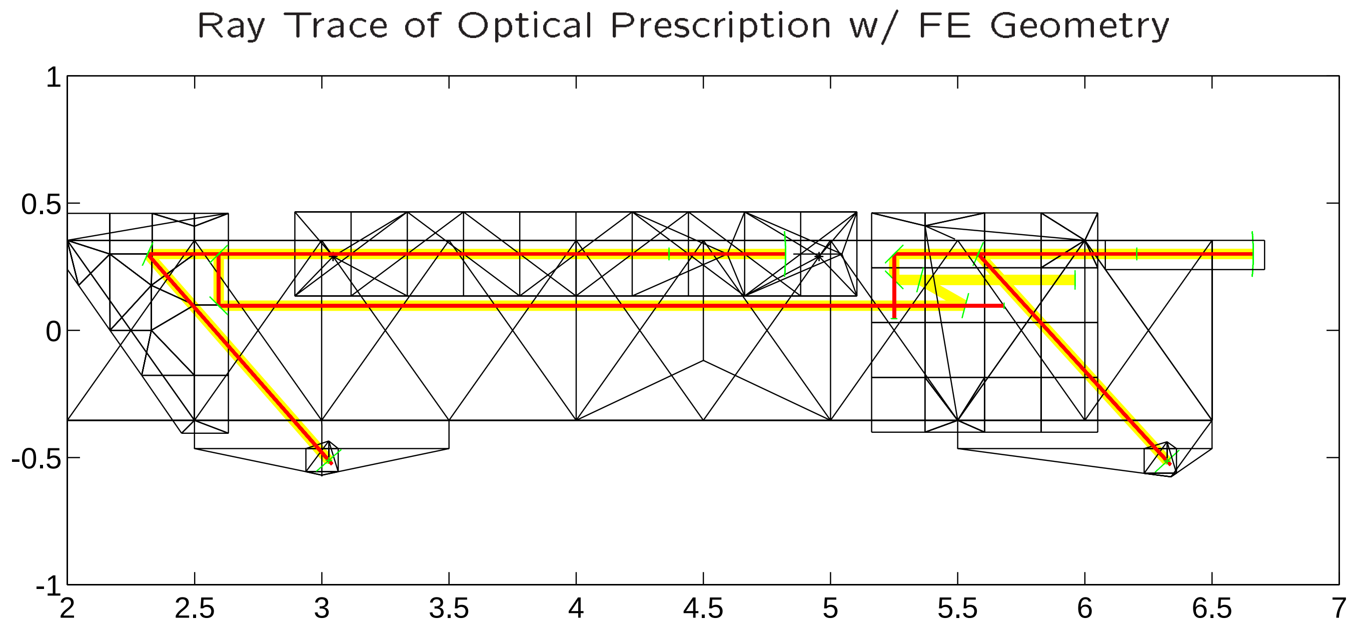
- Finite element description ($d \in R^{2577}$):

$$M\ddot{d} + Kd \;=\; B_f\, f$$

- Incorporation of multi-point constraints from RBEs ($d_n \in R^{1832}$):

$$d = \begin{bmatrix} d_n \\ d_m \end{bmatrix} = G d_n \;\;\Rightarrow\;\; M_{nn}\,\ddot{d}_n + K_{nn}\,d_n = B_{nf}\, f$$

MPI Optical Model



- Optical prescription specifies shapes, positions, and orientations of optical elements.
- Prescription is specified in IMOS relative to the structural model, thereby easing model integration.
- Analytic differential ray trace (COMP) yields linear optical perturbation model:

$$y_{opt} = C_{opt}\, d$$

Model Integration

- Obtain eigensolution of FEM, (Ω, Φ_n):

$$\begin{aligned} \ddot{\eta} + 2Z\Omega\dot{\eta} + \Omega^2\,\eta &= \Phi_n^T\,B_{nf}\,f \\ d &= G\,\Phi_n\,\eta \end{aligned}$$

with diagonal modal damping, Z, experimentally obtained from the testbed.

- Truncate modes above expected disturbance bandwidth (900 Hz), and convert to first-order model:

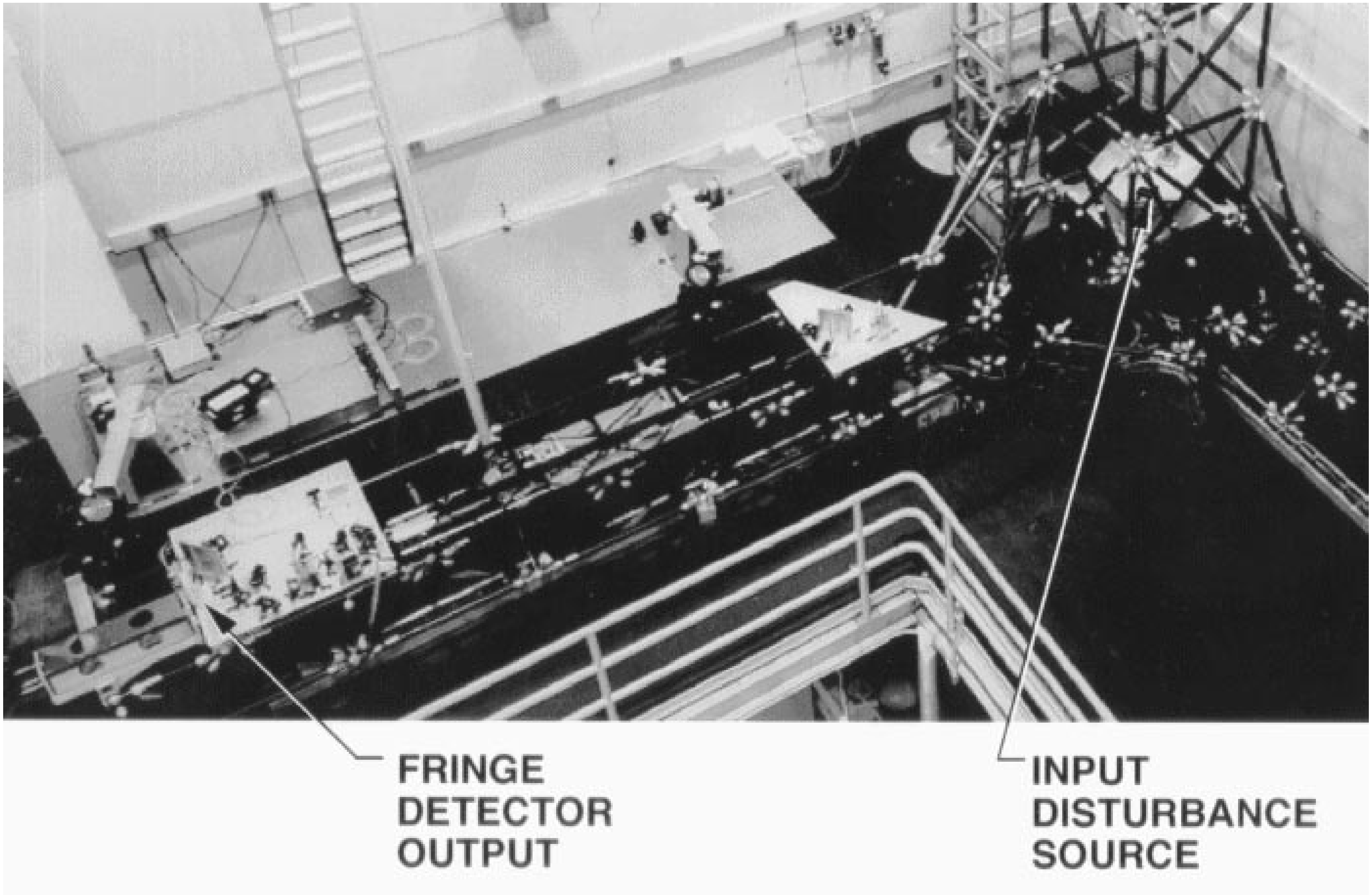
$$x = \begin{bmatrix} \eta_k \\ \dot{\eta}_k \end{bmatrix} \Rightarrow \left\{ \begin{aligned} \dot{x} &= Ax + Bf \\ d &= C_d\,x \end{aligned} \right.$$

with the subscript k referring to the set of 622 kept modes.

- Incorporate linear optical model:

$$y_{opt} = C_{opt}\,C_d\,x \Rightarrow \left\{ \begin{aligned} \dot{x} &= Ax + Bf \\ y_{opt} &= Cx \end{aligned} \right.$$

- Resultant model is amenable to analysis with existing Matlab functions.
  - Input: forces at disturbance location
  - Output: stellar optical pathlength difference


FRINGE
DETECTOR
OUTPUT
INPUT
DISTURBANCE
SOURCE

Validation Metric

- Typically, disturbance has broadband PSD, $\Phi_d(\omega)$, and the performance measure is OPD variation, σ_{opd} :

$$\sigma_{opd}^2 = \frac{1}{\pi}\int_0^\infty |G(\jmath\omega)|^2\,\Phi_d(\omega)\,d\omega$$

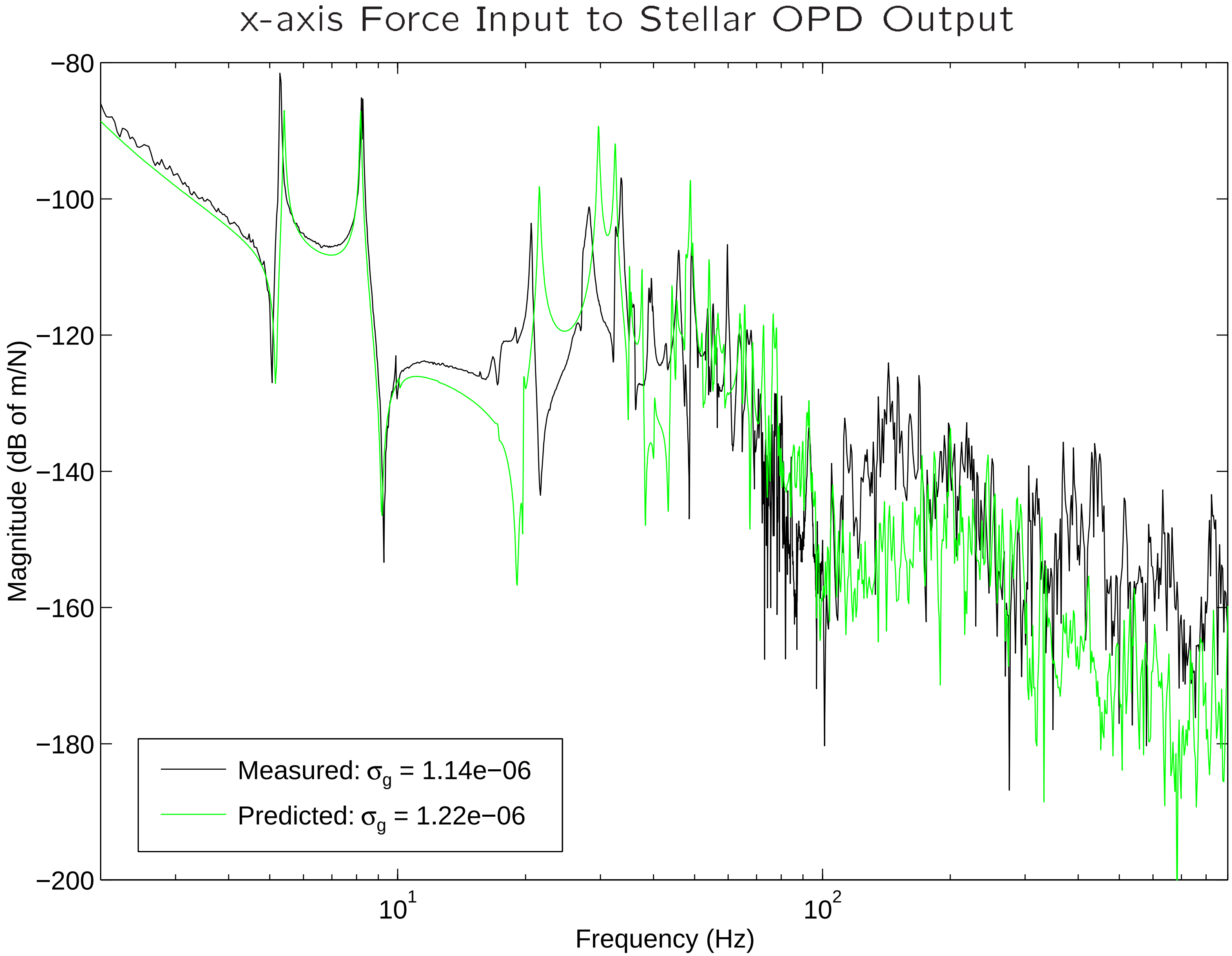
- Generally, an accuracy of a **factor of two** in σ_{opd} is desired.

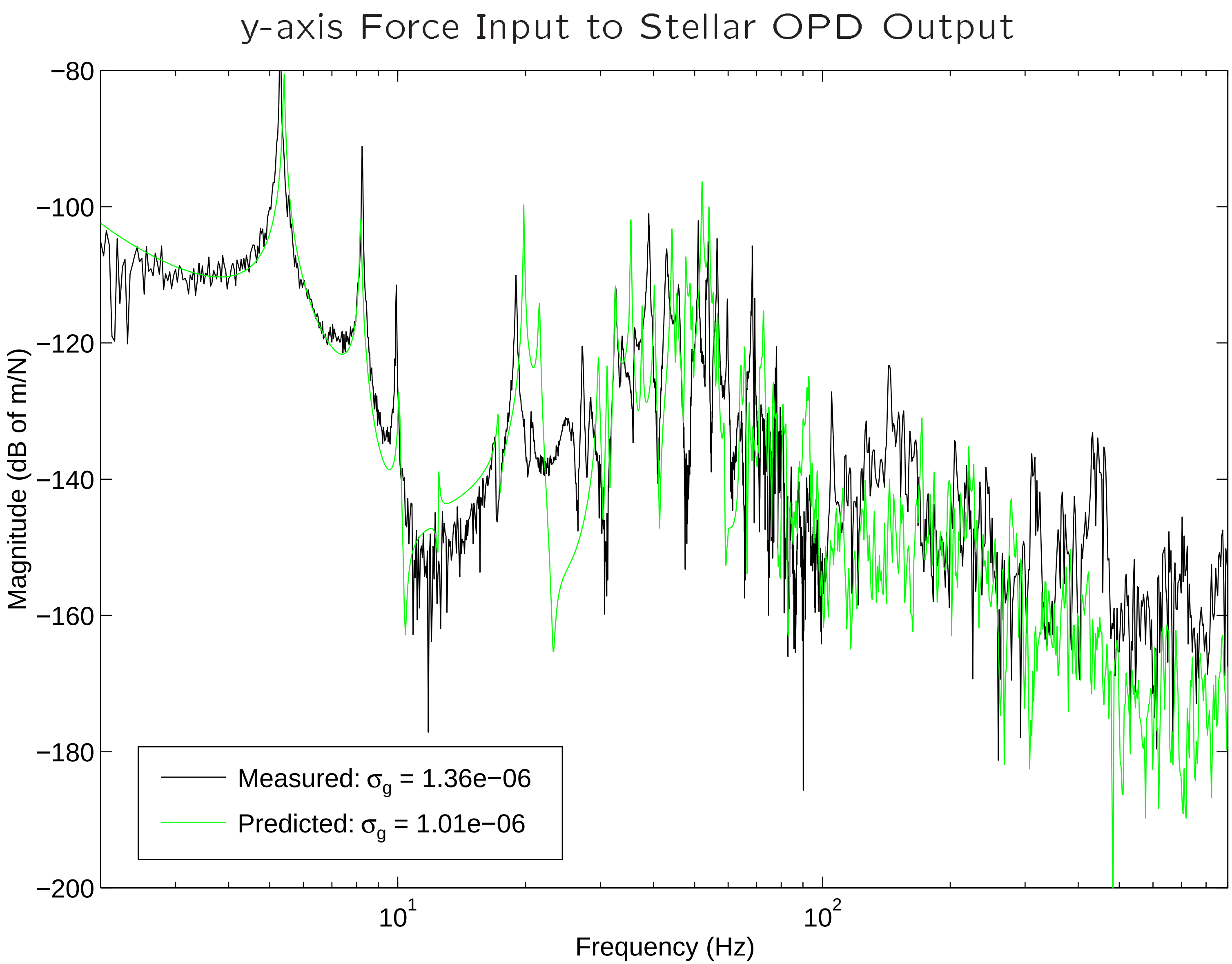
- Use a bandlimited white noise disturbance to characterize the accuracy of the predicted transfer functions in the frequency range of interest ($[\omega_1,\ \omega_2]$):

$$\sigma_g^2 = \frac{1}{\pi}\int_{\omega_1}^{\omega_2} |G(\jmath\omega)|^2\,d\omega$$

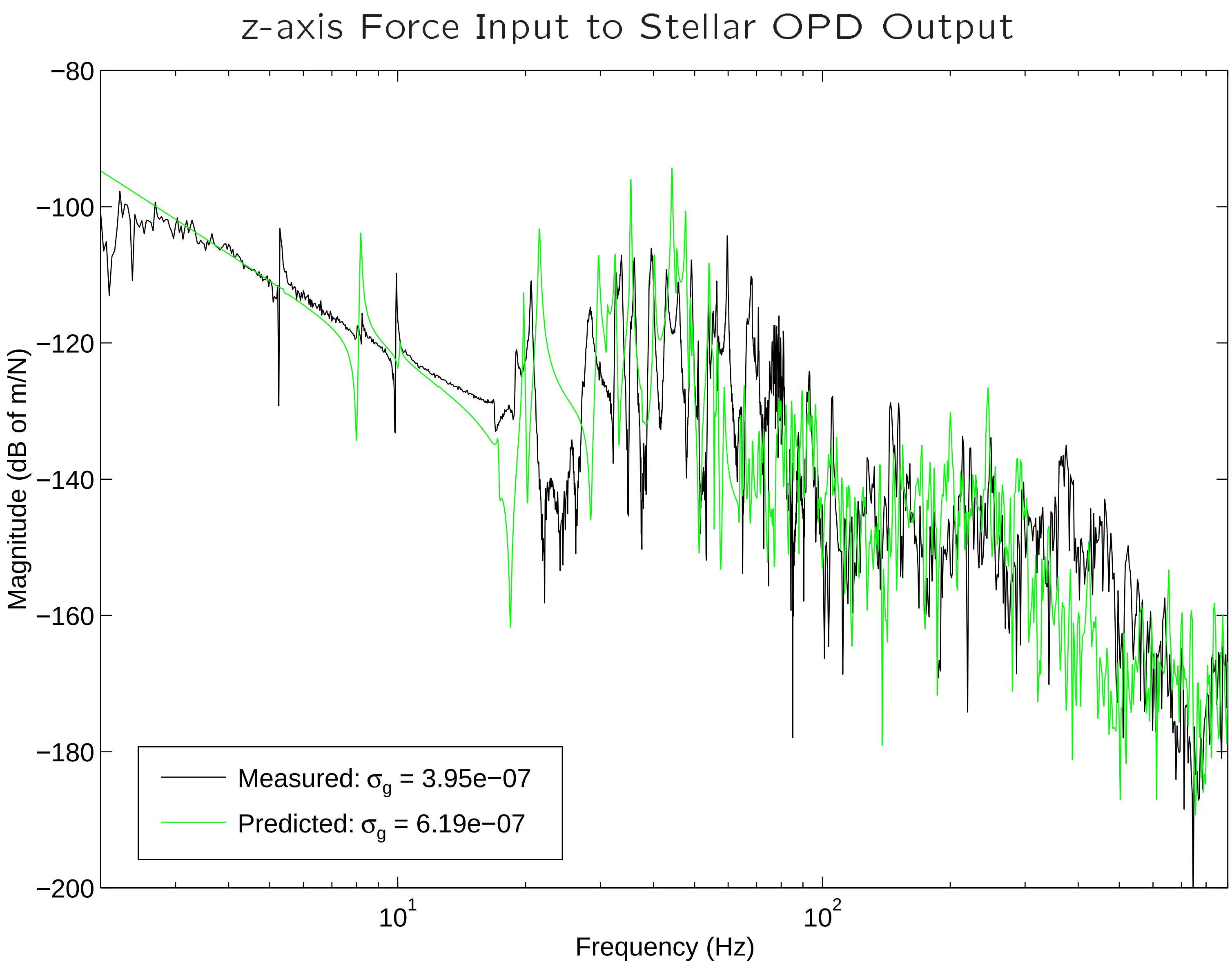
- Apply the factor of two desirement to the ratio of σ_g for the predicted and measured transfer functions:

$$\frac{1}{2} \leq \frac{\sigma_{gp}}{\sigma_{gm}} \leq 2$$


x-axis Force Input to Stellar OPD Output
Magnitude (dB of m/N)
−80
−100
−120
−140
−160
−180
−200
10^1
10^2
Frequency (Hz)
Measured: σ_g = 1.14e−06
Predicted: σ_g = 1.22e−06



y-axis Force Input to Stellar OPD Output
−80
−100
−120
−140
−160
−180
−200
Magnitude (dB of m/N)
10^1
10^2
Frequency (Hz)
Measured: σ_g = 1.36e−06
Predicted: σ_g = 1.01e−06


z-axis Force Input to Stellar OPD Output
Magnitude (dB of m/N)
−80
−100
−120
−140
−160
−180
−200
10^1
10^2
Frequency (Hz)
Measured: σ_g = 3.95e−07
Predicted: σ_g = 6.19e−07

Disturbance Input		σ_g			
		4 - 10 Hz	10 - 100 Hz	100 - 900 Hz	*4 - 900 Hz*
x-axis Force	measured	997	541	70	*1,137*
	predicted	666	1,025	22	*1,223*
	factor	0.67	1.89	0.32	*1.08*
y-axis Force	measured	1,313	360	69	*1,363*
	predicted	864	522	24	*1,010*
	factor	0.66	1.45	0.35	*0.74*
z-axis Force	measured	185	346	50	*395*
	predicted	177	591	47	*619*
	factor	0.95	1.71	0.95	*1.57*

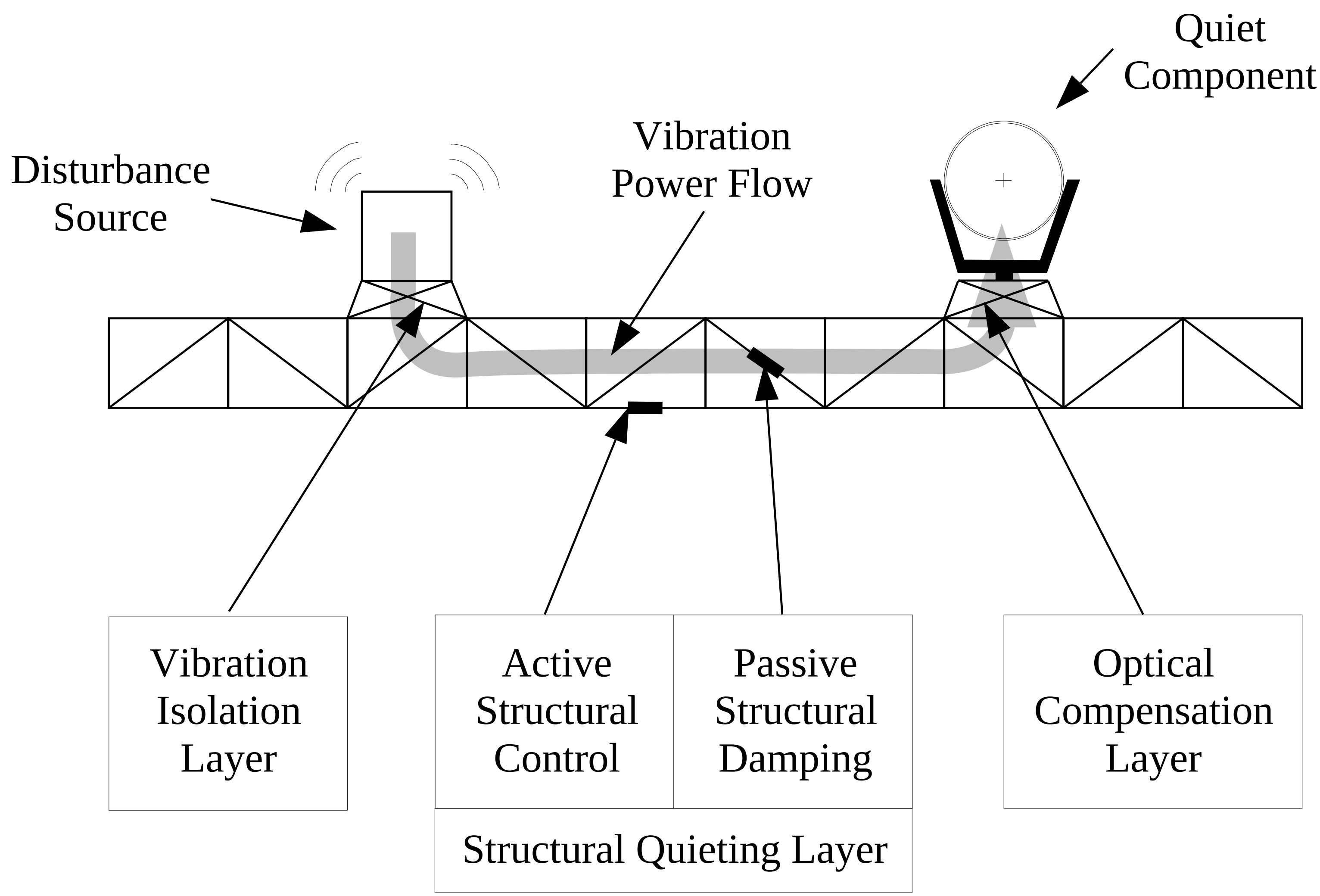
Note: units are absent since the *separate* values are not meaningful. It is the *ratio* that is significant.

Future Work

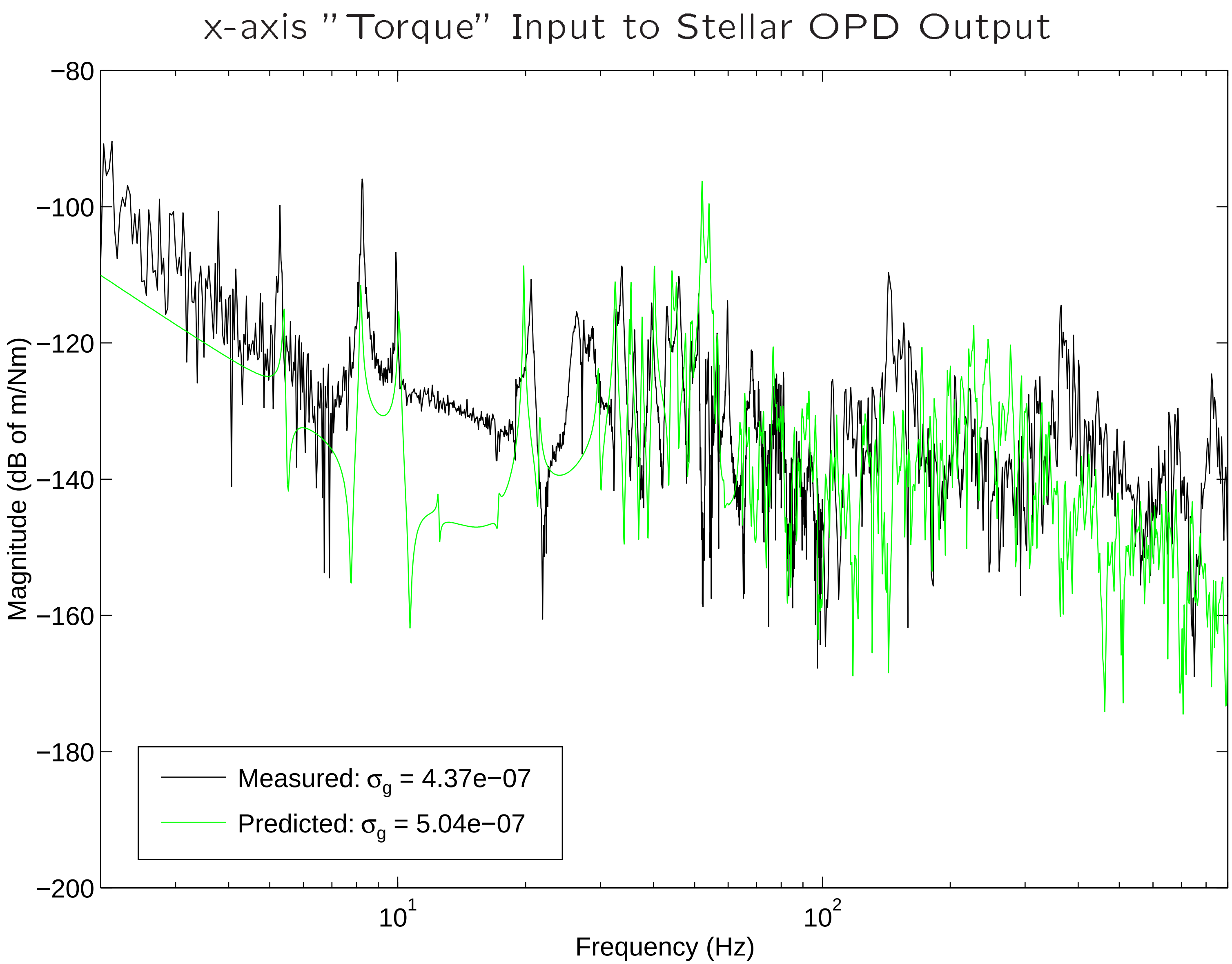
- Validate disturbance torque transfer functions
  - Torques not yet included because of bad measurement approach: torques generated by tandem force shakers.
  - Measurement will be improved by fabrication of torque shaker.
- Validate for various CSI vibration attenuation layers
  - Active optics (draft submitted to ACC 97)
  - Active optics and isolation
- Determine, in retrospect, how much parameter identification and/or model fidelity is needed for valid model.
  - Simple beam model of structure.
  - Rod model of truss structure.
  - Structural model before various parameter identification.
- Time domain validation for particular RWA disturbance input.
  - In lab, generate RWA disturbance for several wheel speeds and measure resultant OPD. Compare with predicted OPD.
  - Combines validation and performance prediction efforts.

Supporting Vugraphs

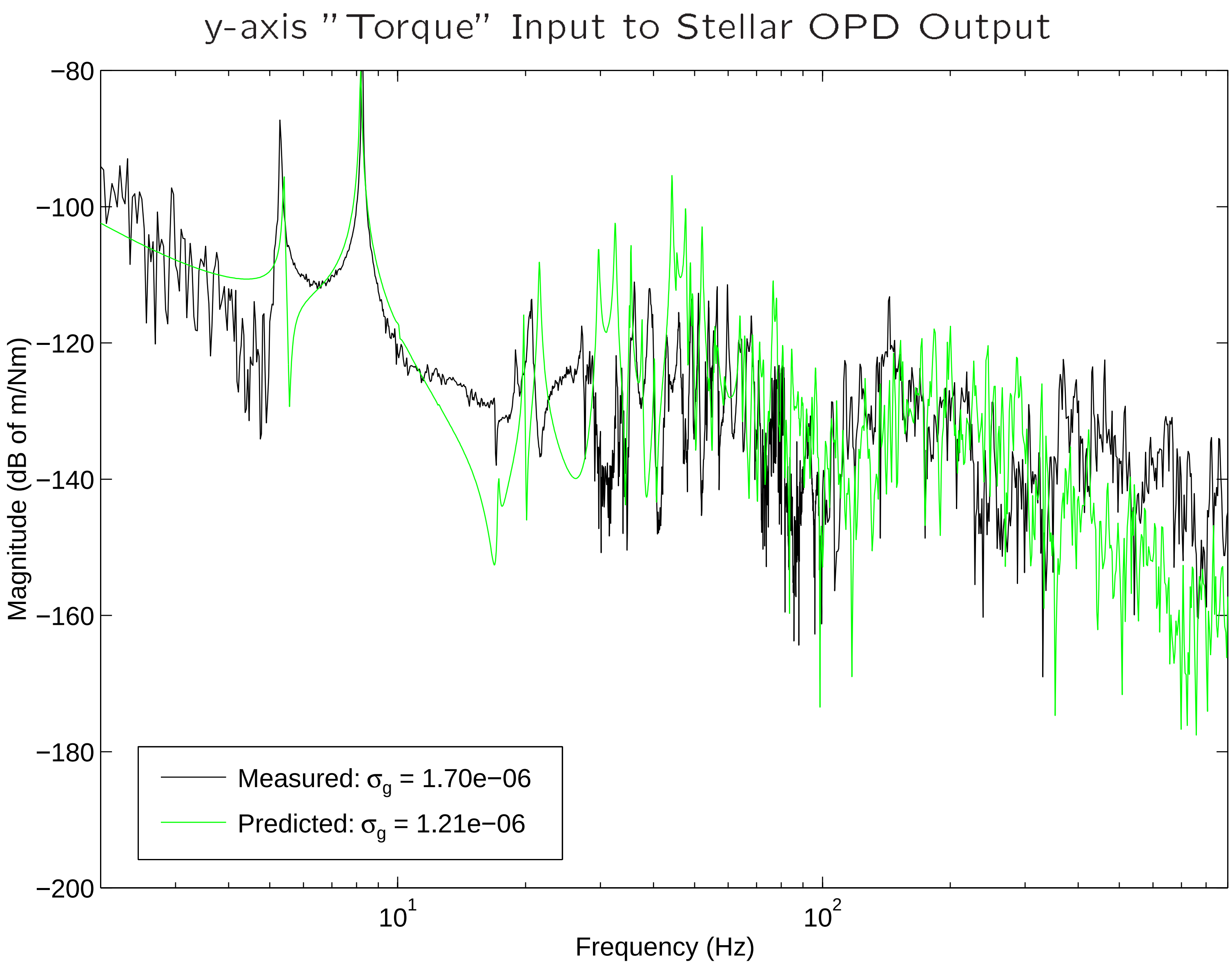
CSI Layered Technology



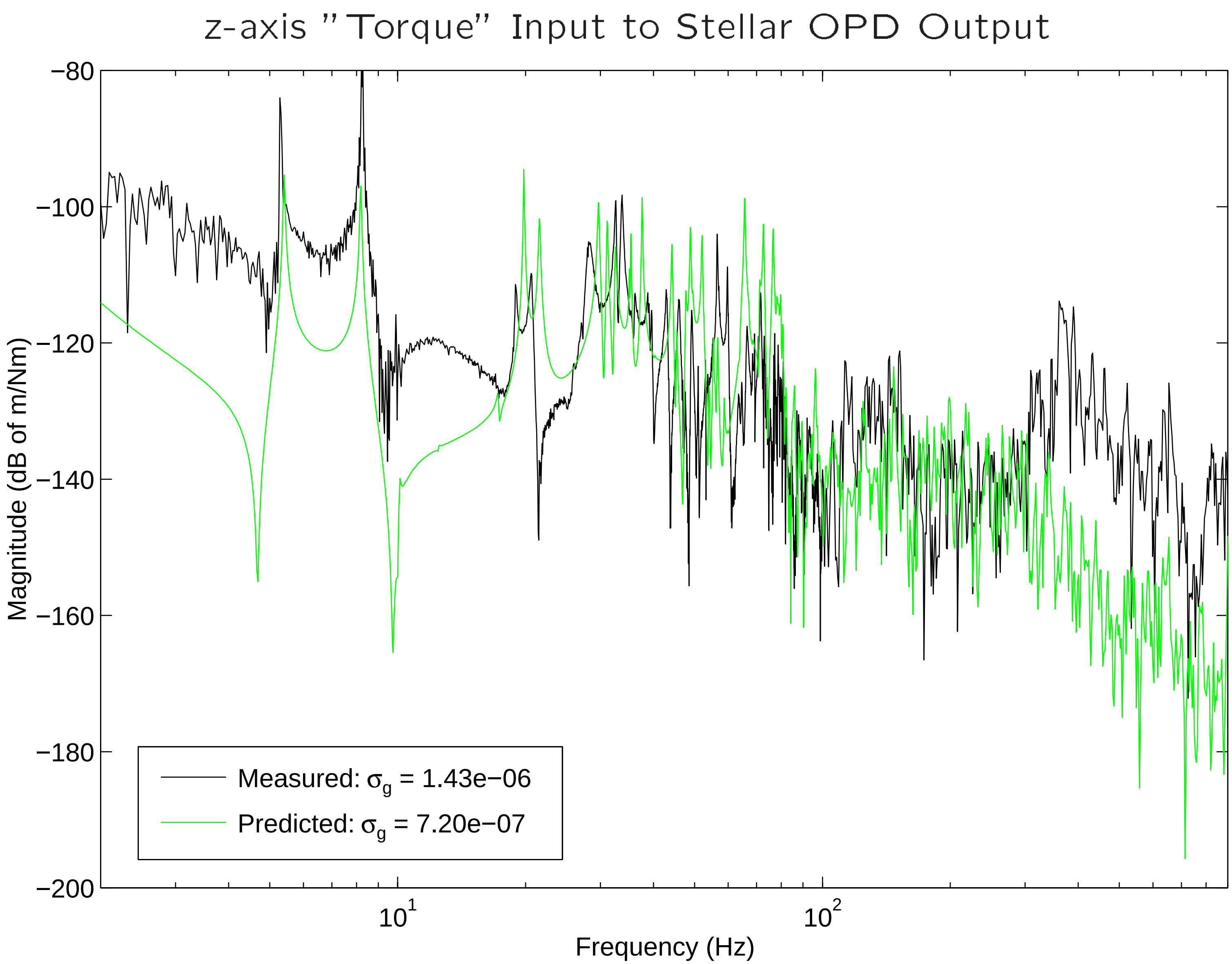
Disturbance TF Comparison



Disturbance TF Comparison



Disturbance TF Comparison



Disturbance Input		σ_g			
		4 - 10 Hz	10 - 100 Hz	100 - 900 Hz	*4 - 900 Hz*
x-axis Torque	measured	196	201	335	*437*
	predicted	44	471	175	*504*
	factor	0.23	2.34	0.52	*1.15*
y-axis Torque	measured	1,667	201	241	*1,697*
	predicted	1,065	542	199	*1,212*
	factor	0.64	2.70	0.82	*0.71*
z-axis Torque	measured	1,292	499	349	*1,429*
	predicted	219	682	73	*720*
	factor	0.17	1.37	0.21	*0.50*

Note: units are absent since the *separate* values are not meaningful. It is the *ratio* that is significant.